Proximity Link Telecommunication and Tracking Scenarios for a Potential Mars Sample Return Campaign

Charles D. Edwards, Jr., Allen H. Farrington, Roy E. Gladden, Charles H. Lee, Robert E. Lock, Brian K. Muirhead, Austin Nicholas, Ryan C. Woolley
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr
Pasadena, CA 91109
818-354-4408
Charles.D.Edwards@jpl.nasa.gov

Orson Sutherland
European Space Agency - European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

Abstract— **A Mars Sample Return (MSR) campaign would involve a series of three flight missions to acquire and cache Mars samples, retrieve those samples and launch them into Mars orbit, and then capture these samples and return them to Earth. Relay communications would be crucial for supporting this campaign, characterized by multiple critical events, complex surface operations, and an on-orbit Mars rendezvous. The existing Mars relay network offers significant capability, and efforts are underway to maximize the likelihood that one or more of these current assets will still be operational in the timeframe of an MSR campaign. In addition, the Earth Return Orbiter (ERO) element of a campaign could serve as a primary relay asset, if it can achieve a useful relay orbit by the time of arrival of the Sample Retrieval Lander mission. We describe key operational challenges of the MSR campaign that would drive the required relay capabilities, and characterize the performance of the existing relay orbiters as well as ERO itself in meeting those relay needs.**

TABLE OF CONTENTS

1. INTRODUCTION

Mars Sample Return represents the next key step in our exploration of the Red Planet. Return of a set of scientifically selected samples to Earth would offer unprecedented opportunities for scientific investigation by allowing the full capabilities of terrestrial laboratories to be applied. A potential MSR campaign encompasses a challenging series of missions, for which relay communications would be essential to ensure mission success. In this paper we highlight the key proximity link telecommunication and tracking scenarios encompassed by the MSR campaign and describe how existing relay assets as well as the Earth Return Orbiter element of MSR can address those needs.

In Section 2, we provide a brief overview of the current notional MSR campaign architecture. Section 3 summarizes the existing Mars relay network infrastructure, including relay-equipped orbiters from both NASA and ESA, and the plans to sustain that capability through the time frame of an MSR campaign. Section 4 then examines individual MSR campaign relay scenarios, including critical event telemetry and tracking support for a Sample Retrieval Lander (SRL) Entry, Descent, and Landing (EDL); surface operations of SRL, the Sample Fetch Rover (SFR) and the Mars 2020 rover; telemetry and tracking support of the Mars Ascent Vehicle (MAV) launch, followed by a summary discussion in Section 5.

2. MARS SAMPLE RETURN ARCHITECTURE

The scientific community has made a strong and compelling case for the return of a set of scientifically selected Mars samples for investigation in terrestrial laboratories on Earth. Such a strategy would enable the application of the full breadth and depth of Earth-based analytical instrumentation towards the objective of advancing our understanding of the Martian system, including its potential for harboring past or present life, its geological and climatological evolution, and both the challenges and the local resources available for future human exploration [1].

The National Research Council's most recent planetary science decadal survey [2] strongly endorsed the objective of Mars Sample Return and placed a caching rover mission, the first element of a multi-mission MSR campaign, as its highest priority flagship mission for the decade 2013-2022. That sample caching mission is now under active development as NASA's Mars 2020 Rover mission and is currently scheduled for launch in July-August 2020.

In April 2018, NASA and ESA signed a Joint Statement of Intent, documenting the two agencies' mutual interest in studying a collaborative MSR campaign which would ultimately return the samples collected by Mars 2020, via a

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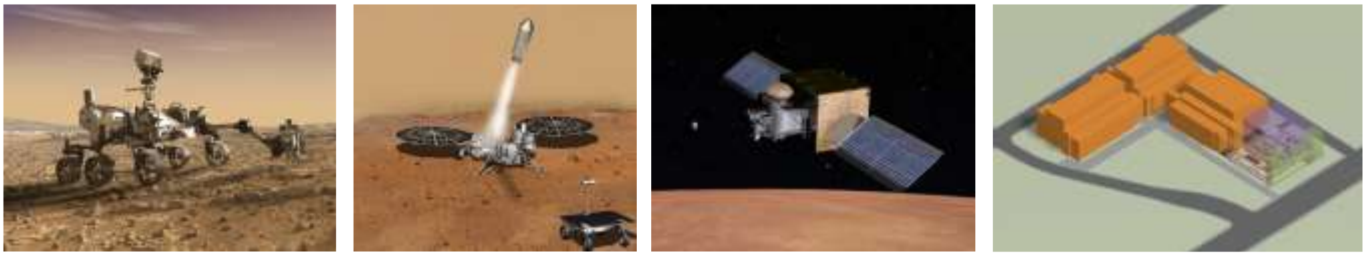


Mars 2020 | Sample Retrieval Lander | Earth Return Orbiter | Mars Returned Sample Handling

Figure 1. Notional MSR Architecture, illustrating three flight elements and one ground element

pair of follow-on mission concepts: a Sample Retrieval Lander and an Earth Return Orbiter.

Figure 1 illustrates the top-level notional MSR architecture proposed for the MSR campaign, composed of three flight elements and one ground element. We briefly describe here each of the campaign elements:

Mars 2020: Mars 2020 [3] is responsible for collecting a scientifically selected set of samples for potential return to Earth, in addition to conducting its own *in situ* science investigations. The instrument suite on the rover will be used to select the most scientifically compelling samples and to provide a comprehensive field context for each collected sample. The rover will carry a set of 42 sample tubes, each capable of acquiring rock core samples of ~1 cm diameter and ~5 cm length. The mission is designed to be capable of acquiring 20 samples during its 1.25-Mars-year primary science phase; additional samples could be collected during a possible extended mission. M2020 will be capable of caching acquired sample tubes in one or more “depots” by dropping them on the Martian surface, for retrieval by a subsequent Sample Retrieval Lander mission. In addition, M2020 can retain a subset of samples onboard, which the rover could itself deliver to a future Sample Retrieval Lander for return to Earth.

Sample Retrieval Lander: The SRL mission [4] would be responsible for retrieving the samples collected by M2020, transferring them to an Orbiting Sample container (OS), and launching the OS into a stable low-Mars orbit. SRL would land in the vicinity of the samples collected by M2020, carrying both a Sample Fetch Rover (SFR) and a Mars Ascent Vehicle (MAV) to the surface. After egress from the SRL, the SFR would retrieve samples from one or more sample depots, where M2020 would have previously cached populated sample tubes, and drive them to the SRL. In addition, M2020 itself can independently deliver any collected samples that it has retained onboard by driving to the SRL and dropping the samples next to the lander.

SRL would then use its robotic sample transfer arm to transfer individual sample tubes, from SFR and/or from M2020, and load them into the OS. The number of sample tubes accommodated in the OS is currently an open trade, and due to engineering constraints may be less than the full set of M2020 samples, so there may need to be some triage and down-selection at this point to select the final set of samples that are loaded onto the OS. The OS would be positioned at the top of the MAV, which would launch from the surface and release the OS into a stable, low-altitude circular orbit for subsequent retrieval and return to Earth.

Earth Return Orbiter: The ERO mission [5] would be responsible for tracking the MAV during its launch, rendezvousing with the on-orbit released OS, capturing the OS onboard the ERO, securely containing the OS to prevent the release of any unsterilized Mars material upon return to Earth, transferring the OS to an Earth Entry Vehicle (EEV), executing a Mars-to-Earth transfer trajectory, and releasing the EEV for entry and landing at a landing site such as the Utah Test and Training Range. Contingent on its arrival time relative to SRL, the ERO could also serve as a telecommunication relay asset for the SRL mission, including provision of critical event telemetry and tracking support durin the SRL’s Entry, Descent, and Landing (EDL), as well as surface relay support for the SRL, the deployed SFR, and M2020 during surface retrieval operations.

Mars Returned Sample Handling: Once the EEV has landed, ground recovery operations would safely secure the EEV and transfer it to a Sample Receiving Facility for biosafety assessment and initial science observations. Once deemed safe, the samples would be transferred to one or more Sample Curation Facilities for long-term preservation and for distribution to terrestrial sample analysis laboratories for ongoing science investigations.

MSR Timeline Options

As noted above, the relative arrival times of the ERO and SRL missions are a key factor in the role that ERO can play as a relay asset supporting the SRL mission. This represents a significant programmatic consideration in the overall MSR strategy. The individual orbiters defining today’s relay network will be operating well beyond their original design lifetimes during a possible MSR campaign. One option would be to deploy a new dedicated relay orbiter in advance of SRL to support the relay needs of that mission. However, that strategy would likely result in a delay of the MSR campaign due to the funding resources required to implement that relay replenishment mission. An alternative strategy is to count on at least one member of the existing relay network to still be operational in the SRL surface mission time frame.

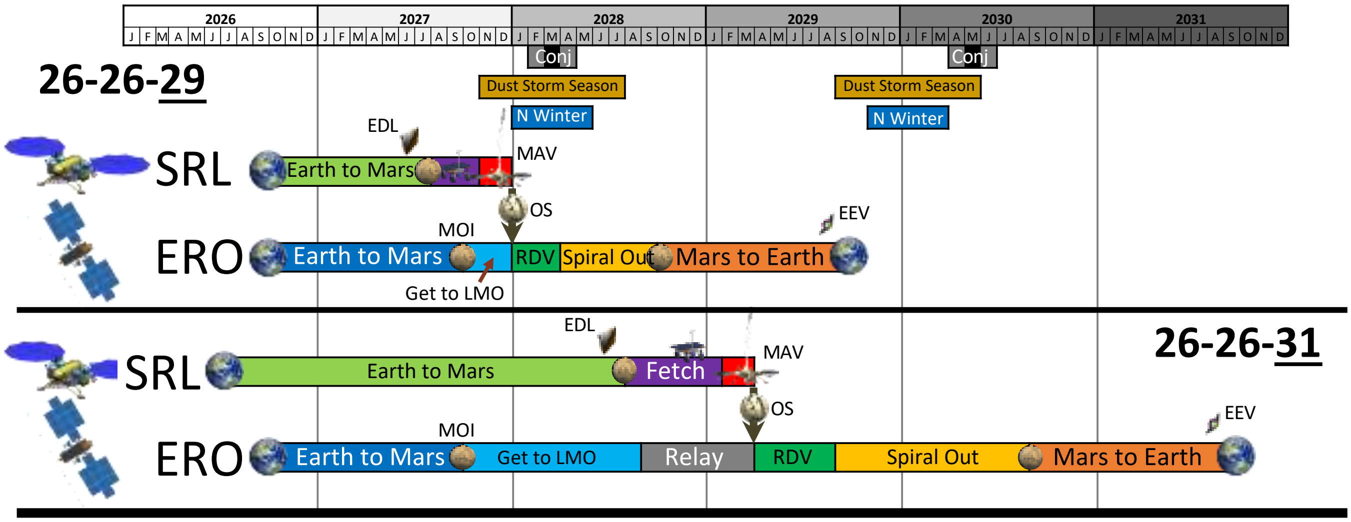


Figure 2: Notional timelines for a 3-year and a 5-year SRL/ERO round-trip scenario

That avoids the cost of a new dedicated relay orbiter, but carries the programmatic risk of dependence on successful extended operations for at least one of the current orbiters. A third option is to design the SRL and ERO missions to ensure that ERO can be on station in time to fully support the relay needs of the SRL mission. That avoids the need for a dedicated relay replenishment mission; should any of the existing network still be operational in that timeframe, that would provide additional relay capability that would enhance SRL surface operations.

Figure 2 illustrates these timeline considerations for two notional MSR scenarios [6]. Details of these timelines are still under active study, and depend on a large number of open design trades, including launch vehicle capabilities, spacecraft masses, orbiter propulsion choices, landing dispersions, roving capabilities, MAV dispersions, orbiter rendezvous capabilities, and other factors.

The top portion of Figure 2 depicts a "fast" MSR architecture, with launch of both the SRL and ERO mission in 2026, and with return of samples to Earth in 2029. In this scenario, the SRL mission utilizes a Type I/II ballistic Earth-Mars transfer for early arrival at Mars, followed by a rapid surface mission in order to complete sample retrieval and MAV launch prior to the arrival of the martian global dust storm season and northern hemisphere winter. In this scenario, the ERO mission utilizes a combination of chemical and electric propulsion; the chemical propulsion stage is used for the initial Mars orbit insertion (MOI) into an elliptical orbit; solar electric propulsion is then used to spiral down to the final 375-km circular orbit, for all but the final elements of the on-orbit OS rendezvous, and for the Mars-to-Earth return trip. A key feature of this "fast" option is that the ERO arrives in time for observing the MAV launch, but well after the SRL's EDL and after much of the SRL surface mission. This scenario would thus depend on relay services from the existing relay infrastructure for support of the SRL EDL and early surface mission.

By contrast, the lower portion of Figure 2 depicts a slower-paced architecture, again with launch of both the SRL and ERO mission in 2026, but with return of samples to Earth in 2031. This scenario delivers SRL on a Type III/IV trajectory in order to arrive after the martian global dust storm season and at the start of northern hemisphere spring; this provides significant benefits in terms of eliminating the risk of a large dust storm, providing increased insolation for a solar-powered lander/rover, and significantly relaxing the timeline for completion of the SRL surface activities. In this scenario, ERO MOI occurs well before SRL arrival; the SRL EDL takes place late during the ERO's spiral down to low circular orbit, enabling ERO to fully support SRL relay, including critical event telemetry and tracking during EDL as well as surface relay during the SRL sample retrieval activities and telemetry/tracking support for the MAV launch. Given these advantages, we focus on this second scenario for the relay support analysis below, with 2026 launch dates for SRL and ERL and a 2031 date for samples returned to Earth.

3. EXISTING RELAY INFRASTRUCTURE AND PLANS FOR EXTENDED OPERATIONS

To evaluate the potential utility of the existing relay infrastructure for supporting the MSR campaign, we review here the capabilities of the current Mars relay orbiters and the steps being taken to maximize the likelihood that they will remain operational through the time frame of the MSR campaign. Table 1 lists key characteristic of the existing suite of Mars relay orbiters, including NASA's Odyssey (ODY) orbiter, Mars Reconnaissance Orbiter (MRO), the Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter, and ESA's Mars Express Orbiter (MEX) and ExoMars Trace Gas Orbiter (TGO). All of these orbiters implement the CCSDS Proximity-1 Space Link Protocol to enable fully interoperable relay services [7,8,9], including interagency cross-support scenarios.

Table 1: Key features of the current Mars Relay Network orbiters.

	ODY	MEX	MRO	MAVEN	ExoMars/TGO
Agency	NASA	ESA	NASA	NASA	NASA
Launch Date	2001	2003	2005	2013	2016
Orbit	400 km 93 deg inclination	298 x 10,100 km 86 deg inclination	255 x 320 km 93 deg inclination	~220 x 4500 km[1] 74 deg incilnation	400 km 74 deg inclination
UHF Transceiver	CE-505 (2)	Melacom (1)	Electra (2)	Electra (1)	Electra (1)
Antenna	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix
Max Data Rate	256 kbps	128 kbps	2048 kbps	2048 kbps	2048 kbps
Transmit Power	12 W	8.5 W	5 W	5 W	5 W
Adaptive Data Rate Capable?	N	N	Y	Y	Y

[1]MAVEN orbit reflects current plan for orbit modification prior to the arrival Mars 2020.

The two longest-operating orbiters, NASA's ODY and ESA's MEX, are not deemed likely to continue operations into the time frame relevant for support of an SRL mission, so we focus here on the three youngest members of the current relay network: MRO, MAVEN, and TGO. Nonetheless, ODY and MEX demonstrate the capability of significant extended operational lifetimes for these relay orbiters; ODY and MEX are in their 18th and 16th years, respectively, of flight operations.

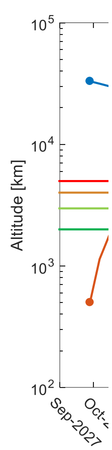
MRO, MAVEN, and TGO all carry NASA's Electra UHF relay transceiver for provision of forward and return link proximity link telecommunication services to relay users at Mars. Electra [10, 11] is a software-defined radio supporting return link data rates of up to 2048 kbps. Electra also supports an Adaptive Data Rate capability in which the orbiter Electra transceiver monitors the signal-to-noise ratio on the user-to-orbiter return link throughout a relay contact and, based on that information, continually sends directives to the user to update the return link data rate to the maximum supportable value, significantly increasing aggregate data return over the pass. Electra currently supports (7, ½) convolutional coding on the return link; efforts are currently underway to implement a Low-Density Parity Check (LDPC) code on the return link for MAVEN and TGO, offering ~3 dB performance improvement; these upgrades are scheduled for upload to both orbiters prior to Mars 2020 arrival. (Due to hardware constraints on MRO's earlier-generation Electra, no LDPC upgrade is planned for that orbiter.)

MRO: Launched in 2005, MRO carries a redundant pair of Electra UHF transceivers for support of relay users [12]. MRO operates in a sun-synchronous near-polar orbit, offering relay contacts at fixed times of day, currently ~ 3 AM and 3 PM Local Mean Solar Time (LMST). The afternoon contacts in particular have proven to be ideal for lander/rover operations, providing end-of-sol telemetry that can be used for ground planning of the next sol's activities.

In spite of already having been in operation for 13 years, MRO is well-positioned for continued operation through the SRL support time frame. The spacecraft has roughly 200 kg of propellant remaining, with annual usage of only ~10 kg/yr. MRO transitioned to All-Stellar ACS mode in March 2018 to preserve remaining IMU lifetime. The mission is actively managing the spacecraft battery to maintain battery lifetime through the 2020's; this may include migration of the orbit node to a later LMST, closer to the terminator, to reduce eclipse durations and associated depth of discharge. The bulk of the spacecraft subsystem redundancy is intact; one exception is the X-band high-rate downlink, where failure of a Waveguide Transfer Switch early in the mission has left just one X-band TWTA able to route a downlink signal to the High Gain Antenna.

MAVEN: This Mars Scout mission carries a single-string Electra payload [13]. Currently operating in a 150 x 6200 km elliptical orbit, with a 74 deg inclination, MAVEN is scheduled to transition to a new relay orbit in advance of the Mars 2020 mission's arrival at Mars, using aerobraking to reduce the orbit apoapsis altitude to ~4500 km to reduce the slant range for relay operations and improve relay performance, and propulsively raise the periapsis altitude to ~220 km to reduce atmospheric drag effects and enable a propellant lifetime through at least 2030. MAVEN's non-sun-synchronous elliptical orbit results in relay contacts that drift in LMST and vary significantly in relay performance. Overall, the spacecraft is in excellent health, with no loss of subsystem redundancy experienced to date.

TGO:



Figure

Table 2: Key Telecom Parameters for MSR Landed Elements

	M2020	SRL	SFR
UHF Transceiver	Electra-Lite	Electra-Lite	QinetiQ
Transmit Power (W)	8.5	8.5	4.0
Coding	(7,½), LDPC	(7,½), LDPC	(7,½)
Max Data Rate (kb/s)	2048	2048	1024
Antenna	Quadrifilar Helix	Quadrifilar Helix	Dipole

Trajectory

The newest addition to the Mars relay network, TGO launched from the Baikonur Cosmodrome on March 14, 2016, executed MOI in Oct. 2016, and then carried out a period of aerobraking to achieve its current 400-km, 74-deg inclination circular orbit in Feb. 2018. Like MAVEN, TOG's non-sun-synchronous orbit results in relay contacts that drift in LMST. TGO carries a redundant pair of Electra UHF transceivers, contributed by NASA to the ESA ExoMars mission. TGO relay operations have begun, with successful relay support to NASA's Opportunity and Curiosity rover. ESA reports that the spacecraft is in excellent health, with adequate propellant to support operation through 2030.

4. MSR Relay Scenarios

Sample Retrieval Lander Entry, Descent, and Landing

EDL represents a critical event – a short-duration, complex mission activity where mission success depends on nominal execution of a large number of spacecraft events, and where a wide range of anomalies can result in loss of mission. Accordingly, both NASA and ESA have established policies to acquire critical event telemetry and tracking data during critical events such as EDL, in order to enable fault reconstruction in the event of a loss-of-mission anomaly. This strategy has been successfully applied to landings by the Mars Exploration Rovers, which utilized "semaphore" tones on its X-band DTE link to convey low-bandwidth information roughly every 10 s during EDL, as well as the Phoenix Lander, Mars Science Laboratory, and the ExoMars Schiaparelli Lander EDL events, which added UHF proximity links to acquire higher-rate EDL telemetry, with rates of 8-32 kbps. In the latter case, telemetry and tracking data collected by TGO were crucial in reconstructing and fully diagnosing the Schiaparelli EDL event, providing valuable confirmation of the many successful elements of EDL and definitively identifying the anomaly that led to loss of the Lander, informing future EDL implementations. Similar EDL coverage strategies are already planned for the InSight Lander, Mars 2020, and ExoMars Rover and Surface Platform landings.

In many respects, SRL's EDL is in family with these prior and planned EDL events. While one or more current relay orbiters could be positioned to provide geometric coverage of SRL EDL, assuming continuing operational lifetime, ERO itself can serve as the primary EDL support asset if it has already arrived at Mars. For the notional 5-yr SRL/ERO round trip scenario (shown in the bottom of Figure 2), ERO arrives at Mars in Oct 2027 and then carries out an EP-based spiral-down period to achieve the final 375-km operational circular orbit at a 25 deg inclination. As shown in Figure 3, immediately after the chemical-propulsion-based Mars Orbit Insertion, ERO is in a highly elliptical 500 x 32,000 km orbit. EP is then used to lower the apoapsis while simultaneously raising periapsis to achieve a near-circular orbit, and then continues to gradually spiral down to the final 375-km circular orbit. At the time of SRL arrival, around Aug/Sep 2028, ERO is still at an orbit altitude of ~2000 km. This is sufficiently low, and the resulting communication slant range is sufficiently short, to support 8 kb/s telemetry on the UHF link from SRL during its EDL. ERO's spiral-down trajectory will need to be controlled to ensure that both the orbit ascending node and the orbit true anomaly enable visibility of SRL's EDL trajectory from atmospheric entry through landing.

If MRO, MAVEN, and/or TGO are also still operational at the time of SRL arrival, it may also be possible to position one of those orbiters to provide additional critical event coverage for SRL's EDL.

Surface Sample Retrieval Operations

Relay support would be crucial to the success of the MSR surface sample retrieval, which entails a number of challenging operational scenarios. After SRL landing, the lander would image its immediate surroundings, identifying any nearby rock/slope hazards, and then execute egress of the SFR off of the lander. Once deployed, the SFR must rapidly traverse to the site of one or more Mars 2020 depot cache locations and retrieve a collection of sample tubes for return to the SRL. Depending on the landing dispersion of SRL, the round-trip SFR drive distance for this sample retrieval activity could be as large as 15 km. In parallel, during this period the M2020 rover will independently traverse to the SRL, carrying the subset of acquired sample tubes retained on M2020. Both the SFR and M2020 mobility operations will drive the need for timely return of decisional data each sol to support drive planning; based on prior rover operational experience, minimum data return of ~100 Mb/sol would be needed, with delivery to ground planners with latencies of no more than a few hours, in order to support one-sol planning cycles that are key to efficient surface operations. SFR tube

Table 3: Average per-sol relay data volume metrics for ERO support to SRF, M2020, and SRL, from 2000-km altitude (immediately after SRL landing) and from final low-altitude circular orbit.

	ERO @ 2000 km				ERO @ 380 km			
	SFR		M2020 or SRL		SFR		M2020 or SRL	
Data Vol (Mb)	Nadir	Boresight	Nadir	Boresight	Nadir	Boresight	Nadir	Boresight
Best Pass	166	191	787	191	388	191	826	191
2nd-Best Pass	160	179	745	179	368	179	770	179
3rd-Best Pass	142	166	659	166	331	166	740	166
4th-Best Pass	98	127	431	127	282	127	716	127
5th-Best Pass	62	90	208	90	200	90	546	90
6th-Best Pass	19	30	64	30	59	30	175	30

pickup operations, as well as tube transfer from SFR and M2020 to SRL, would be highly challenging operational phases where robust relay communications will be crucial to mission success. Finally, the number of collocated assets poses an additional challenge to relay support, with SRL, SFR, and M2020 all within the same coverage footprint during each relay overflight. Our baseline assumption is that an Electra-equipped ERO, like the existing MRO/MAVEN/TGO orbiters, will only be able to support a single user at a time.

ERO relay support to the MSR surface operations can begin immediately after SRL landing. Detailed relay performance depends on the implementation of the UHF relay payloads both on ERO and on the landed MSR assets. As an initial reference, we assume that ERO would utilize the same Electra UHF Transceiver that is flying on MRO, MAVEN, and ExoMars/TGO. We assume that the NASA SRL would use the same Electra-Lite Transceiver that M2020 uses, and that the ESA-supplied SFR would incorporate the same QinetiQ UHF transceiver flown on the 2016 ExoMars/Schiaparelli Lander and slated for flight on the 2020 ExoMars Rover and Surface Platform spacecraft. Table 2 summarizes the key telecom parameters of the M2020, SRL, and SFR relay payloads.

Figure 4 summarizes relay coverage from ERO to SRL for two cases: a) an initial 2000-km circular orbit, representative of the ERO orbit state immediately after SRL landing, with 3-4 months of EP-based spiral-down operations still remaining, and b) operation from the final 375-km circular orbit. The plots indicate the Local Mean Solar Time (LMST) of individual passes over a period of multiple sols. The relatively low (25 deg) inclination of the ERO orbit results in excellent relay coverage for the low-latitude landing sites under consideration for Mars 2020. (For this analysis we assume a landing site at Jezero Crater; the nearby Northeast Syrtis site would have nearly identical coverage metrics.) In the 2000-km orbit, with an orbit period of roughly 3.5 hrs, ERO views the landing site on ~6 consecutive orbits as Mars rotates, followed by a gap of roughly 7 hours. The orbit node precesses relatively slowly at this altitude, drifting towards earlier LMST with a period of 160 sols. In the final low-altitude circular orbit, the landing site continues to receive ~6 overflights each sol over a series of consecutive orbits, at lower slant range and shorter duration, and with a longer gap time of roughly ~12 hours. At this lower altitude, the nodal precession rate is considerably faster, with the local time of contacts drifting through 24 hrs in just 40 sols.

To quantify the data return possible with ERO, we have conducted detailed relay telecommunication link analyses using JPL's Telecom Orbit Analysis and Simulation Tool (TOAST) [14]. We characterized data volume via ERO for SFR, SRL, and M2020, based on the relay payload assumptions summarized in Table 3. Analysis was performed for two scenarios: ERO operating at 2000-km altitude, reflecting the performance achievable immediately after SRL landing while ERO is continuing its spiral-in phase, and ERO operating in its final 380-km circular orbit. For each case, we considered two options for pointing of ERO's UHF relay antenna, assumed to have 6 dBic of gain: a) nadir pointing, and b) boresight pointing, with the boresight direction steered to the surface user throughout the overflight. (With a spacecraft body-fixed UHF antenna, boresight pointing will require slewing of the ERO spacecraft during the pass. An additional consideration during the spiral-in phase is the capability to perform relay while thrusting; it may be necessary to interrupt the EP thrusting to point the UHF antenna.) Overflight durations were limited to 30 min maximum duration, reflecting current operational considerations due to surface user energy/thermal constraints, as well as orbiter operational constraints, and a 3-dB link margin was assumed for all links.

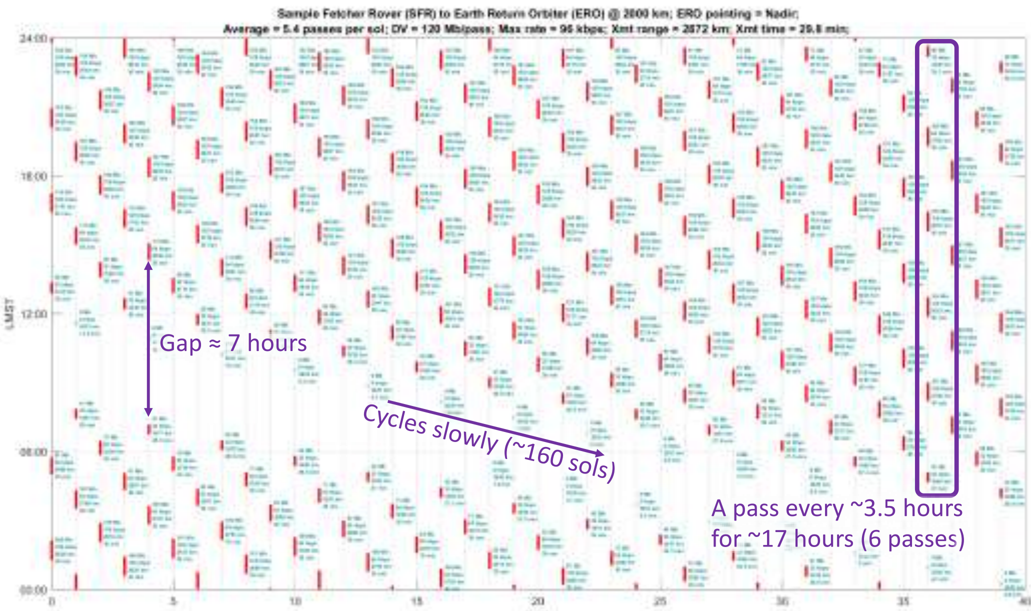
To assess ERO's capability to support multiple relay passes per sol, we quantified the ranked performance of the six best passes each sol. Table 3 presents the results of this ERO relay performance analysis. Overall, ERO's excellent relay coverage translates into robust relay support for the multiple surface spacecraft engaged in MSR surface operations. From the initial 2000-km orbit that ERO will be operating in at the time of SRL landing, SFR can achieve average data return of 142 Mb or more from any of the best three passes each sol, assuming nadir orbiter pointing. For M2020 and SRL, performance is much higher, with the best three passes each offering average data return of over 650 Mb. The Electra-Lite-equipped landers offer higher data return based on several factors: a) higher transmit power; b) enhanced LDPC coding [15]; c) higher maximum data rate; d) improved antenna pattern. Boresight pointing offers only limited improvements, as the off-nadir angles to the lander are relatively small from this higher altitude.

Performance improves even more once ERO completes its spiral-in and achieves its final 380-km circular orbit. SFR data return increases by more than a factor of two, due to the lower slant range and higher data rates attainable at this lower ERO altitude. For M2020 and SRL, the increases are more modest, due to saturating the link at the highest supportable data rate of 2048 kb/s. Boresight pointing does offer more benefit at this lower ERO altitude, due to the increased off-nadir angles to the landing site over the course of an overflight. However, such pointing may be more challenging to obtain at this lower altitude, due to higher angular rates.

Table 4: Relay data volume metrics for relay support to SFR, M2020, and SRL by the existing relay orbiters MRO, MAVEN, and TGO

	SFR			M2020/SRL		
Data Vol (Mb)	MRO	MAVEN	TGO	MRO	MAVEN	TGO
Best Pass	206	173	302	383	613	706
2nd-Best Pass	145	82	184	273	367	484
3rd-Best Pass	7	41	33	7	142	79

a)



b)

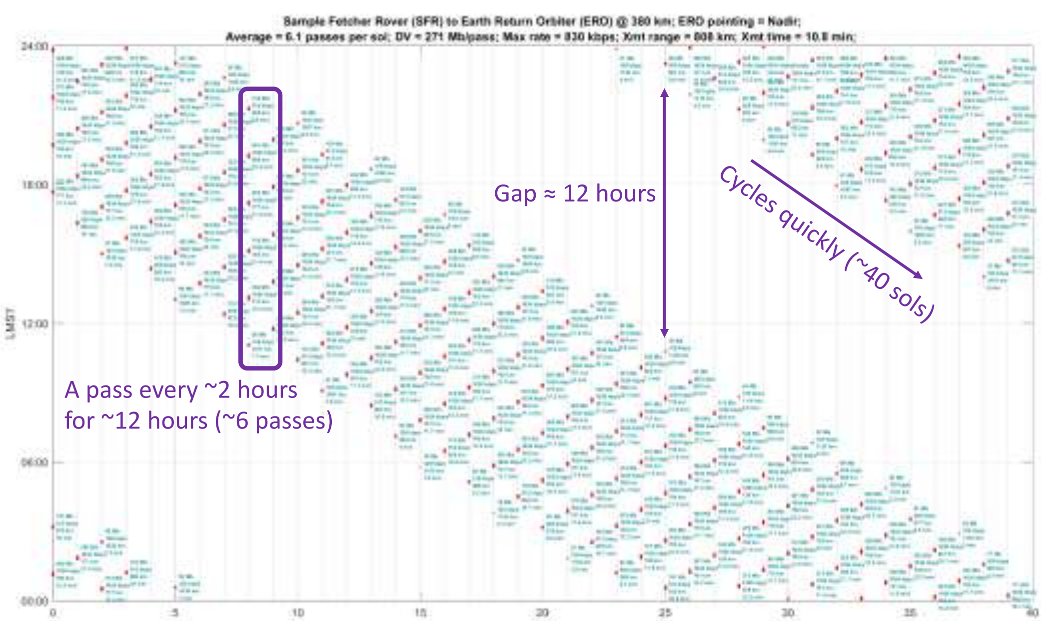


Figure 4: ERO-SFR relay coverage a) immediately after SRL arrival, during ERO spiral-in at 2000-km altitude; b) from final low circular ERO orbit, achieved ~ 3-4 months after SRL EDL. (Annotations indicate pass data volume, mean pass data rate, mean pass slant range, and pass duration.)

We have also assessed the relay performance metrics for MRO, MAVEN, and TGO in support of SFR, M2020 and SRL. Such support could be used to augment ERO relay services, potentially providing relay contacts during gap periods in ERO coverage each sol, and also represent a contingency capability should ERO relay services not be available. For instance, in the event of a failure of ERO, support from the existing relay orbiters could enable safe and stable Mars orbit, prior to arrival of the Martian winter and dust storm season that would potentially terminate the SRL/SFR surface missions, thereby allowing retrieval of the on-orbit samples by a subsequent ERO recovery mission.

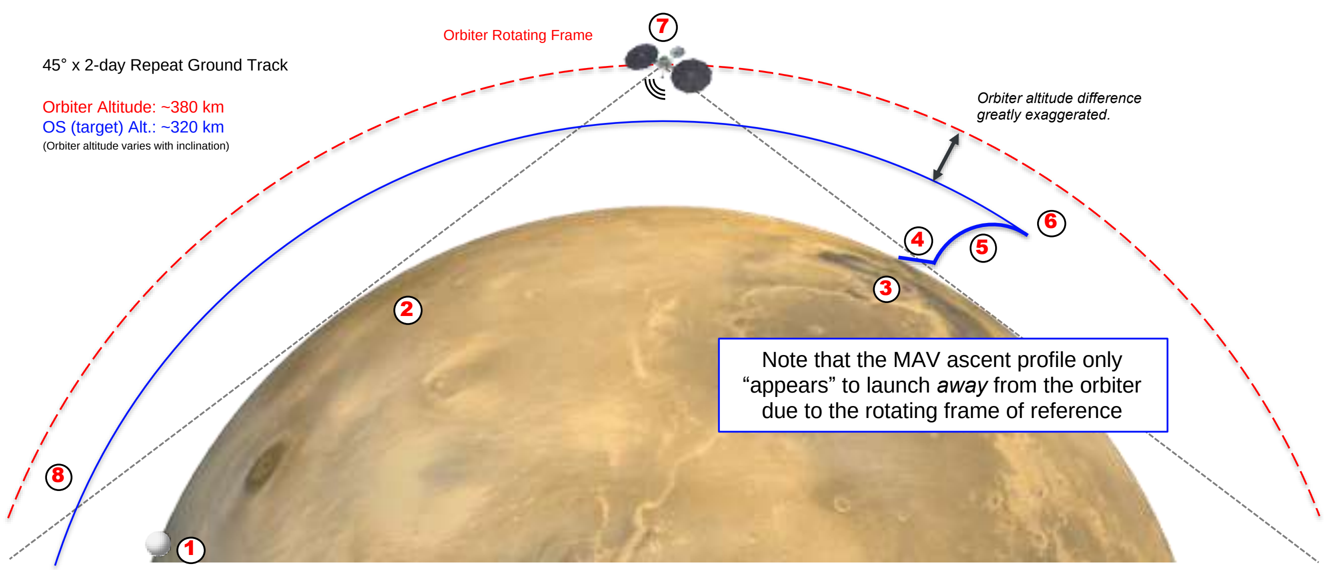
The higher inclinations of the MRO, MAVEN, and TGO orbits result in significantly fewer contacts per sol, typically limited to just 2-3 useful passes per sol. Table 4 reports the resulting TOAST analysis relay metrics for relay support to SFR, M2020, and SRL from the existing relay network. The results for the best pass each sol are generally in-family with the results for ERO in its final orbit. However, for the existing orbiters performance falls off precipitously after the best-two passes each sol, due to the more limited overflights and generally lower elevation angles experienced in those passes. This suggests that support to the full MSR surface mission by just one of the existing assets would be challenging, in terms of fully supporting all three assets on the surface each sol. Such a contingency scenario would likely require splitting relay passes to support more than one lander on a given overflight – a capability that has been developed for support of the InSight Lander mission, whose landing site is close to the Curiosity Rover's Gale Crater site. Such a capability may also be used in support of the ExoMars Rover and Surface Platform mission, with a collocated lander and rover each requiring relay service.

However, with ERO operational, any of these existing orbiters would offer significant added robustness for MSR surface operations, with increased aggregate data return and opportunities for additional contact times throughout each sol.

Mars Ascent Vehicle Launch and On-Orbit Rendezvous Operations

Once the retrieved samples have been delivered to the SRL, transferred to the Orbiting Sample container, and placed atop the MAV, the MAV would be launched into a low circular Mars orbit, where the OS would be released for subsequent rendezvous and capture by the ERO. While the details of the MAV/OS orbit target are still under study, we consider here a target orbit with the same 25 deg inclination as ERO, but with a somewhat lower target altitude of 320 km.

Figure 5 illustrates the notional MAV launch sequence, as viewed in an ERO-rotating reference frame. The MAV is readied for launch several days in advance. On the intended day of launch, ERO and SRL can optionally perform a "go/no-go" handshake shortly after ERO rises at the SRL landing site to confirm ERO readiness to perform MAV launch coverage. (In the event ERO fails to confirm readiness, the launch would be scrubbed and targeted for a subsequent sol.) The MAV then launches, shortly before ERO sets as viewed from SRL, and performs an initial 2-min



Event	Time	Event	Time
1 MAV Ready for Launch	L-2d	5 Ascent Coast Phase	L+15m
2 MAV-Orbiter In-View (Go / No Go)	L-20m	6 2nd Burn / OS Separation	L+16m
3 MAV Launch	L-0	7 OS Passes under Orbiter	L+15h*
4 Ascent 1st Burn	L+2m	8 OS Occulted by Mars	L+39h*

* @ nominal MAV altitude

Figure 5: Notional MAV Launch Scenario (as viewed in an ERO-rotating reference frame)

burn, followed by a 13-min coast phase. (These times are notional, corresponding to a candidate hybrid propulsion MAV design.) A second 1-min burn then executes to circularize the MAV orbit, at which time the OS is released from the MAV. At this point, the OS is in a lower-altitude orbit, relative to ERO, and proceeds to slowly drift under ERO, passing directly under the orbiter ~15 hrs after MAV launch (for a nominal MAV orbit insertion) and remaining in view until ~39 hrs after launch.

Launch of the MAV represents the first firing of an ascent rocket on the surface of another planet. As such, this is another key critical event, where it will be essential to acquire telemetry and tracking data during the launch, capable of supporting diagnosis and fault reconstruction in the event of a MAV launch failure. In addition, the MAV tracking and telemetry data provide an important initial estimate of the OS orbit. The current reference concept for the OS does not include any RF capability; the ERO must ultimately locate the OS in orbit using passive optical sensors (i.e., a suite of long-range, medium-range, and short-range cameras). Acquisition of the MAV telemetry, with its reported IMU data stream, along with the Doppler signature observed on the MAV-ERO UHF link, provide an initial estimate of the OS orbit state, which will be used to constrain the angular search space that must be searched by the ERO's long-range camera for initial OS acquisition.

To support this, the MAV would include a capability to transmit a modulated UHF telemetry stream throughout the launch phase. Details of the MAV transmit capability, including transmit power and antenna design, are not yet determined. However, similarities of this MAV launch support with prior EDL critical event support suggest that data rates of ~10 kb/s should be supportable with ~5 W of transmit power and a broad wraparound antenna pattern. Future work will assess the specific engineering telemetry needed to support potential fault reconstruction in the event of a launch anomaly and to provide information on the final MAV orbit. Note that in the event of a successful MAV launch, additional telemetry can be transmitted after OS release to provide a significantly larger volume of recorded engineering telemetry regarding the performance of the MAV.

5. SUMMARY

Relay communications would play a critical role in the successful execution of an MSR campaign. The current Mars relay network, including orbiters from both NASA and ESA, provides highly capable, interoperable relay services. MRO, MAVEN, and TGO are all healthy and have the potential for operations through the envisioned period of a potential MSR campaign. Nonetheless, each would be operating well beyond its original design lifetime; this provides a strong motivation for MSR campaign architectures that allow ERO to be in a relay-capable orbit prior to the arrival of SRL, allowing ERO to provide critical event communication support to SRL's EDL, and to support the full SRL surface retrieval mission.

The simultaneous operation of three landed assets – M2020, SFR, and SRL - during the surface phase of MSR poses new relay challenges. However, ERO's low-inclination orbit would enable increased relay contacts with the MSR landing location, providing adequate contact opportunities and data return for all three assets in spite of the assumed single-access link capability. (Nonetheless, addition of a multiple-access relay capability to ERO's relay transceiver would offer significant benefits in this multi-lander scenario.)

ERO relay support would also play a critical role during the MAV launch, acquiring critical event tracking and telemetry data to support fault reconstruction in the event of a launch anomaly while providing MAV IMU telemetry and Doppler tracking data to generate an initial estimate of the MAV/OS orbits, key to supporting the optical search for the OS by ERO.

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8. BIOGRAPHY

Charles (Chad) Edwards, Jr. *is the Manager of the Program Formulation Office in the Mars Exploration Directorate at the Jet Propulsion Laboratory, where he also serves as the Directorate's Chief Technologist. He received an A.B. in Physics from Princeton University and a Ph. D. in Physics from the California Institute of Technology.*

Allen H. Farrington *is a graduate of Duke University and Caltech, with degrees in Electrical Engineering and more than 30 years of experience in hardware and software development. Since coming to JPL, Allen has managed a variety of instrument and flight developments for Earth Science, Planetary Science, and Technology Development. Currently, Allen is the Manager of the Mars Ascent Vehicle technology development efforts working to mature the required technologies needed for the future Sample Return Lander MAV. Among other honors, Allen is a recipient of the JPL Award for Excellence and the JPL Explorer Award (2008). Other than spaceflight, Allen's interests tend towards College Hoops and Ballroom dancing.*

Roy Gladden *is the Manager of the Mars Relay Network Office at the Jet Propulsion Laboratory. He previously served as the Multimission Relay Operations Lead for the Mars Program Office and the Multimission Ground Systems and Services organization at JPL, and earlier led the Mission Planning and Sequencing Team for the Mars Reconnaissance Orbiter Project. He received both a B.S. and M.S. in Mechanical Engineering from Utah State University.*

Charles H. Lee *is a Professor of Applied Mathematics at the California State University Fullerton and a faculty part time staff member in the Communications Architectures and Research Section (332) at the Jet Propulsion Laboratory. He received his Doctor of Philosophy degree in Applied Mathematics in 1996 from the University of California at Irvine. Before becoming a faculty member in 1999, he spent three years as a Post-Doctorate fellow at the Center for Research in Scientific Computation, Raleigh, North Carolina, where he was the recipient of the 1997-1999 National Science Foundation Industrial Post-Doctorate Fellowship. His research has been*

Computational Applied Mathematics with emphases in Control, Fluid Dynamics, Smart Material Structures and Telecommunications and Biomedical Engineering.

***Robert E. Lock** received his B.S. degree in Mechanical Engineering from Cal Poly, San Luis Obispo in 1985. He has been with JPL for more than 27 years. He currently leads orbiter mission formulation studies for the Mars Exploration Program Office at JPL. He has been Mission Manager for the JPL payloads on the ExoMars Trace Gas Orbiter mission, lead mission planner for Mars Reconnaissance Orbiter mission and mission planning team chief for the Magellan Mission to Venus. He was the lead systems engineer for the Jupiter Europa Orbiter mission study and has led systems engineering, operations design, and aerobraking design for Mars Scout proposals. His career started with work on ISS, Strategic Defense Initiative, and Magellan spacecraft development at Martin Marietta Aerospace in Denver Colorado.*

***Brian K. Muirhead** has worked on numerous spacecraft and technology projects, including Galileo, SIR-C, and MSTI-1, since coming to NASA's Jet Propulsion Laboratory in 1978. He was responsible for the design, development, test, and launch of the Mars Pathfinder spacecraft that landed successfully on Mars on July 4, 1997. He served as Project Manager of the Deep Impact Project from November 1999 to November 2002. In November 2002, he became the Chief Engineer of the Mars Science Laboratory mission and in August 2004 he became Chief Engineer of JPL. In February, 2007 Brian was named Program Systems Engineer for the Constellation Program, and in 2014 he became the Project Manager of the Asteroid Redirect Robotic mission. He is currently leading the MSR campaign architecture and pre-project efforts. He received his BS in Mechanical Engineering from the University of New Mexico in 1977 and an MS in Aeronautical Engineering from Caltech in 1982. He is the recipient of NASA's Exceptional Leadership Medals for his work on Mars Pathfinder and Constellation.*

***Austin Nicholas** received a B.S. degree in Aerospace Engineering from University of Illinois at Urbana-Champaign in 2011 and an S.M. in Aeronautics and Astronautics from the Massachusetts Institute of Technology in 2013. He currently works for JPL in the Project Systems Engineering & Formulation Section. His primary assignment is in the Mars Program Formulation Office developing mission architectures and vehicle concepts for Mars Sample Return. Recent work has included solar electric propulsion spacecraft with co-optimized flight systems and trajectory and sample retrieval rovers. At MIT, he worked on attitude and cluster control for a formation-flight Cubesat mission using electrospray propulsion and architecture exploration for low-cost human missions to the lunar surface.*

***Ryan Woolley** received a B.S. in Physics-Astronomy from Brigham Young University, a M.S. in Astronautical Engineering from USC, and a Ph.D. in Aerospace Engineering from the University of Colorado. He has been with JPL since 2005. Ryan began his tenure as a systems engineer in the Mars Mission Concepts group and has since transferred to the Inner Planets Mission Analysis group. He has worked on nearly all aspects of the Mars Sample Return campaign and has developed many tools to design and evaluate mission designs and architectures.*

***Orson Sutherland** is currently the Study Manager for Mars Sample Return Earth Return Orbiter, within the European Exploration Envelope Programme, HRE-XE Directorate of Human Spaceflight and Exploration at ESA's European Space Research and Technology Centre. Prior to that he has served as the Mercury Transfer Module and Solar Array Development Manager for ESA's BepiColombo mission to Mercury. He received his PhD in Plasma Physics and Ion Optics from the Australian National University in 2004.*